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Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy (DISAA)

THESIS TITLE

Development and evaluation of a detailed, process-based crop model for giant reed

Doctoral Thesis

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Development and evaluation of a detailed, process-based crop model for giant reed

Doctoral Thesis

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Doctoral Thesis in Agricultural Ecology

XXVI Cycle, Academic Year 2012-2013

Dedication – İthaf

I dedicate my thesis to My Mother and My Father. There are no words to express my love and my respect for them. Thank you for your support, your prays and your endless love. GOD always protect you.

Tezimi anneme ve babama ithaf ediyorum. Onlara olan sevgimi ve saygimi anlatacak kelimeler yok. Desteğiniz, dualarınız ve sonsuz sevginiz için teşekkür ederim. ALLAH her zaman sizi korusun.

Yours sincerely - Saygılarımla,
Sevim Seda YAMAÇ

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I would like to express my appreciation for all the moments that I shared with friends in Cassandra group and DISAA department, and I will keep them in my memory long after I leave the place.

Finally, thanks to GOD for my life through all tests in the past three years. You have made my life more bountiful. May your name be exalted, honored, and glorified.

Yours sincerely,

Sevim Seda YAMAÇ

Yamaç, S. S., 2013. Development and evaluation of a detailed, process-based crop model for giant reed. Ph.D. Thesis, University of Milan.

CREDIT EVAULATION

Courses:

- Scientific writing and communication.
- Numerical models for simulation.
- Statistic
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Attendance at international/national congress:

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Attendance at seminars:

“Measuring the drivers of global climate change: Using quantum cascade lasers to quantify atmospheric greenhouse gases”. 4 April 2011, University of Milan.

“Earthworms, soil and Darwin”. 2 May 2011, University of Milan.

“Energy efficiency in collective irrigation facilities: water users' associations” 4 May 2011, University of Milan.

“Land degradation and combating desertification in dry areas”. 12 September 2011, University of Milan.

“Bioenergy in Latin America: status and perspectives in Brazil”. 30 Mrach 2012, University of Milan.

“Life Cycle Assessment: First approaches to application of agro-food and agro-energy”. 19 December 2012, University of Milan.

“Monitoring agro-ecosystems with remote sensing: experiences and future oppurtunities of optical and SAR satellite data” 6 February 2013, University of Milan.

“Genetic dissection of peach fruit quality traits”. 27 February 2013, University of Milan.

“Innovation Day” 13 March 2013, Research Centre for Industrial Crops, Bologna.

“Advanced technologies for the management and analysis of qualitative and quantitative aspects of agricultural production”. 3 July 2013, University of Milan.

“Water management and Nonpoint Source Pollution”. 7 October 2013, University of Milan.

Poster presentation:

Stella, T., Francone, C., **Yamaç, S. S.**, Ceotto, E., Confalonieri, R. Reimplementation and reuse of the Canegro model: from sugarcane to giant reed. AgMIP 4th Annual Global Workshop. 28-30 October 2013, New York, USA.

Publications:

Stella, T., Francone, C., **Yamaç, S. S.**, Ceotto, E., Confalonieri, R., 2014. Reimplementation and reuse of the Canegro model: from sugarcane to giant reed. Comput.Electron. Agric., submitted.

Francone, C., **Yamaç, S. S.**, Stella, T., Ceotto, E., Pagani, V., Pilu, R. S., Confalonieri, R. , 2014. Arungro: giant reed growth and productivity model. Europ. J. Agronomy, to be submitted.

Capelli, G., **Yamaç, S. S.**, Stella, T., Francone, C., Paleari, L., Confalonieri, R., 2014. Are advantages from partial replacement of corn with energy crops undermined by climate change? A case study for Arundo donax in Lombardy (Northern Italy), Biomass Bioenerg, to be submitted.

ABSTRACT

The aim of the thesis is the development of a process-based model for the simulation of giant reed growth and productivity under a variety of climatic and management conditions.

Arundo donax L. (giant reed) is a perennial C3 grass native to Asia and naturalized to the Mediterranean area. Being part of the second generation biofuel crop (i.e., non-food, cellulosic biomass feedstock for ethanol or combustion), *Arundo d.* is characterized by high yield potential with low requirements in terms of soil, fertilizers, and water. Therefore giant reed is attracting interest as an alternative energy source and dedicated research studies are continuously increasing.

The re-implementation of the sugarcane (*Saccharum officinarum* L.) model Canegro (DSSAT v4.5) in a framework-independent component was starting point for the development of the *Arundo donax* L. model (i.e., Arungro). The Canegro component was effectively extended and adapted for giant reed because of several morphological and physiological features shared with sugarcane.

The newly developed Arungro model was calibrated and evaluated by means of two dedicated field monitoring under a number of crop ages and management conditions. The model performed reasonably well especially for the estimation of the aboveground biomass.

The investigation of the impact of climate change on *Arundo donax* L. production was carried out by applying the Arungro model in a case study area in the Po valley area. This was the first attempt in evaluating future non-feed and non-food crop productivity.

Keywords: *Arundo donax* L., climate change, Arungro, crop model, model reuse.

CONTENTS

GENERAL INTRODUCTION

1.1. Background

The climate change impacts studies on social and economic development are rapidly increasing in the last years. According to the Intergovernmental Panel on Climate Change (IPCC) global fossil fuels use have increased extremely since 1850. Therefore growth in carbon dioxide and other gas emissions occurs together with energy demand enhancement.

Renewable energies use represents an important opportunity for developed countries to reduce greenhouse gas emissions thus mitigating climate change risks. Alternative energy services effectively supported the success of the Millenium Development Goals for the social and economic development easing the access to energy and contributing to secure the energy supply itself (IPCC, 2011). Among the available renewable energies (e.g., solar energy, wind energy, geothermal energy), this thesis will focus on bioenergy, in particular from non-food crops.

In this context ethanol, biodiesel, and biogas are the three major bioenergy products. Ethanol and biodiesel are used as transportation fuels, with ethanol also applied as raw product in the chemical industry. Therefore, ethanol production can play a particularly important role in the permutation process from petroleum-based to biomass-based sustainable economies. These energy sources are produced by using agricultural yields (e.g., maize, sugarcane, and sugar beet) as starch, sugar, and lignocellulosic biomasses (Yuan et al., 2008). For example, *Arundo* d. produced 299 litres of ethanol per tonne of stem dry matter biomass, in a process time of less than 24 hours. This equates to 11,000 L ha^{-1} of bioethanol from *Arundo* d. from 40 t ha^{-1} of dry tops per year, compared to 4,400 l ha^{-1} from corn kernels, 4,600 l ha^{-1} from switch grass and 8,800 l ha^{-1} from sugarcane (Williams et al., 2008).

The changing agro-ecological conditions are directly affecting agriculture and food security. At the same time, these conditions can compromise the availability of renewable energy crop sources, in terms of impact on biomass production. Mitigation strategies become thus necessary also in the bioenergy field

From a modeling point of view, a recent literature review presents the 14 models nowadays used to simulate the productivity of bioenergy crops: 11 for herbaceous, one for herbaceous-woody crop, and two for simulating woody perennial crops (Surendran Nair et al., 2012). These models are both specifically developed and adapted from existing ones, showing a variety of approaches to simulate crop growth and timing. Generally, they run at a daily time step, with some of them run hourly and few at annual timescale, depending on the detail of the simulated processes.

1.2. *Arundo donax* L.

Arundo donax L. (giant reed, Poaceae family) is a rhizomatous and perennial tall reed with C3 pathway for carbon assimilation. There is no agreement about location of the area where it originated. Some evidence support the hypothesis that the origin started in the Mediterranean region (Zeven and Wet, 1982; Wagner et al., 1999) whereas other study suggested that it originated in Asia without hybridization with other *Arundo* d. species, due to its sterility nature (Mariani et al., 2010). This species have been cultivated throughout Asia, southern Europe, north Africa, and the Middle East for thousands of years (Lewandowski et al., 2003) and has been planted widely in North and South America and Australasia in the past century (Perdue 1958, Zohary 1962). Giant reed is an asexually reproducing species. Viable seed production is very low and its propagation is mainly via rhizome division and stem pieces spreading. The latter is favored by the crop proximity to streams, drains and other wet environment, since water is fundamental in the first year (i.e., establishment) of the crop. The crop can grow in all type of soil, ranging from heavy clays to loose sands and gravely soils and in warm temperate and tropical regions (Perdue, 1958, Wynd et al., 1948).

From the agronomic point of view, *Arundo* d. can reach average height of 2 to 8 m, with peak of 10 m under non-limiting conditions. The leaves are 30 to 70 cm long and 5 to 7 cm wide (Pilu et al., 2012). Stems are hollow and 2-3 cm in diameter with growth rate of 4 to 7 cm day^{-1}(Mirza et al., 1958). The flowers are straight and feathery between March and late summer (Csurhes, 2009). The rhizomes – large and flashy – are close to the soil surface and the roots are able to reach 5 m in depth (Frandsen, 1997). The fresh matter can reach 100 t ha^{-1} yr^{-1} under ideal environmental conditions (Shatalov and Pereira, 2001) whereas dry matter yields may reach 30-40 t ha^{-1} even under notably limiting conditions (e.g., wastewater, Williams et al., 2009; heavy metal irrigation water, Papazoglou, 2007).

This information was mainly retrieved in the last decades during giant reed studies on: crop control (especially in West America, Dudley, 2000), ethanol or combustion production (Jeon et al., 2010; Nassi o di Nasso et al., 2010), and water treatment and phytoremediation (Mirza et al., 2010).The interest for bioenergy application derived mainly from its high yield potentiality with minimum input requirements. The observation of a multi-years field in central Italy effectively showed the low degree of the crop dependence on fertilization attesting crop suitability to the Mediterranean conditions (Angelini et al., 2005).

Other secondary economical applications of giant reed use include wind-break, soil erosion control, saline ground, electrical energy, fishing rods, medicine, musical instruments, reclamation, garden ornamental, paper production, and forage. In Italy, this species is well-known since 1930 for industrial production (Facchini, 1941).

The literature availability of models simulating *Arundo* d. biomass production is poor and limited to experimental relationships for phenological and biometric evaluations (Graziani and Steinmaus 2009; Spencer and Ksander, 2009; Pompeiano et al., 2013) or structural approaches (Thornby et al., 2007). From the solely modeling point of view, the crop is particularly suited due to its decidedly low genetic variability, thus supporting the application of a single calibration parameter set able to reproduce the crop behavior under different climatic and management conditions.

1.3. Objective and framework of the research

The objective of the thesis is the development of a crop model simulating the effect of different climatic and management scenarios on giant reed productivity in terms of biomass. With this aim, the research addressed the following issues:

- the re-implementation of a detailed model for sugarcane growth and development (i.e., Canegro DSSAT v4.5);
- the adaptation of the Canegro model for the simulation of giant reed (i.e., the Arungro model);
- the collection of a dedicate dataset for the study of Arundo d. behavior for a variety of crop ages;
- the calibration and validation of the Arungro model by means of the observed data;
- the application of the newly developed model for a climate change study in the Po valley (Northern Italy).

1.4. Outline of the thesis

The development of this thesis was characterized by four main phases, mainly of modelling nature with a minor experimental investigation.

In a preliminary step, a literature overview was necessary to investigate (i) the behavior of *Arundo d.* under Mediterranean conditions, (ii) the state of art of crop models. In particular, this work allowed to exclude the suitability of a generic crop model for the simulation of giant reed and suggested the reuse of a detailed sugarcane model (i.e., Canegro) as a starting point for the implementation of the *Arundo d.* model. The two crops effectively share some important traits related to the growth processes.

The following phase was dedicated to the re-implementation of the Canegro model (DSSAT v4.5 version, Jones et al., 2008) in a component following a framework-independent architecture. The reason to exploit this kind of technology was found in the feasibility of the component reuse and extension by third party.

The implementation of the giant reed model (i.e., the Arungro component) was a direct outcome of the application of this technology, as the Arungro component share the 80% of the Canegro approaches. The main issue of this phase was represented by the calibration and validation of the newly developed model. With this aim, a field survey was carried out during the last year of the work, by monitoring the behavior of three different ages of *Arundo d.* through dedicated state variables.

The last part of the thesis concerned the application of the Arungro model to investigate the impact of the future climate scenarios on the productivity of *Arundo d.* The criteria to select the study area were (i) the possible future deficit on maize production, and (ii) the presence of bioenergy processing plants, and (iii) the livestock pressure (i.e., low risk of competition between feed and no feed crop destination).

1.5. Synopsis

Chapter 2 presents the re-implementation and reuse of the Canegro model in a software component. Generally software design does not provide for model reuse indirectly forcing third parties to re-implement existing models instead of adapting them to new needs. The newly developed Canegro component was able to reproduce the DSSAT version performances. The high reusability of the component was showed by its extension for the development of the *Arundo* d. model. The latter effectively inherited almost 70% of the Canegro code.

Chapter 3 presents the Arungro giant reed growth and productivity model. The component was calibrated and validated in two sites of Northern Italy between 2009 and 2012, with measured data of leaf area index, aboveground biomass (both leaf and stem), and stem height and density. Model performances resulted reasonably satisfactory, in particular when comparing measured and simulated aboveground biomass.

Chapter 4 intend to be an exploratory study for the evaluation of the climate change impact on potential productivity of giant reed in an intensive maize-based area of the Po valley where corn is expected to experience unfavorable conditions for growth in the near future. A dedicated simulation environment was developed and in-silico experiments were performed using Arungro. Due to large adaptability of this plant to nutrient and water shortage, the simulations were performed under potential conditions without compromise the adherence to the real system. Climate change scenarios were derived for the IPCC AR4 emission scenarios A1B and B1 and two global circulation models (Hadley3 and NCAR).

REIMPLEMENTATION AND REUSE OF THE CANEGRO MODEL: FROM SUGARCANE TO GIANT REED

Tommaso Stella, Caterina Francone, Sevim Seda Yamaç, Enrico Ceotto, Roberto Confalonieri

Software availability:

Name of software: UNIMI.Crop.Canegro

Available at: http://www.robertoconfalonieri.it/Canegro/CanegroSDK.zip

Developers: Caterina Francone, Tommaso Stella, Sevim Seda Yamaç

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Submitted to: Computer and Electronics in Agriculture. (2014).

Reimplementation and reuse of the Canegro model from sugarcane to giant reed

2.1. Abstract

Model reuse can be limited by software design, which often forces third parties to completely rewrite new versions of existing models before adapting them to new needs. This tendency removes resources from the development and improvement of models, and from the extension of their domain, leading to the proliferation of software sharing large part of the algorithms. Component-oriented paradigm allows to overcome these limitations, facilitating massive model reuse and extension. This study presents the application of these principles to the reimplementation of the sugarcane (*Saccharum officinarum* L.) model Canegro (DSSAT v4.5) in a framework-independent component following the BioMA architecture. The potential for reuse and extension of the component is here demonstrated by its straightforward adaptation for giant reed (*Arundo donax* L.), a promising energy crop that shares several morphological and physiological features with sugarcane. The new component – extending the original sugarcane one – was effectively developed by inheriting about 70% of the Canegro code. The Canegro component is distributed via a Software Development Kit that includes documentation of code and algorithms, and the source code of sample applications illustrating how to use and extend the component.

Key words: Model reuse, BioMA, Canegro, Giant reed, Arungro.

2.2. Introduction

Despite the advantages of model reuse and extension are well known and widely recognized within the international modeller community (Holzworth et al., 2010), the design of agro-environmental models often prevents – to a large extent – these activities, forcing third parties interested in modifying an existing model to re-implement it from the beginning (Donatelli et al., 2008). This time-consuming process often removes resources otherwise available for model improvement; moreover, it often leads to solutions again characterized by a low level of extensibility. In other cases, reimplementation leads to new versions of a model that are extensible but tightly coupled to specific frameworks, and this generates dependences that, in turn, limit the model reusability in other simulation environments (Donatelli et al., 2012). Resources needed for reimplementation increase with model complexity and this, coupled with the difficulties in improving or extending the way processes are formalized, often restricts the opportunity to revise and improve agro-ecological models only to their original developers.

The component-oriented paradigm allows to overcome these limitations favouring model reuse by limiting dependencies, specifying interfaces, and encapsulating the algorithms in discrete units (Szyperski, 2002). As a consequence, models implemented in framework-independent libraries can be effectively used, composed and improved by third parties (Argent, 2005; Confalonieri et al., 2013) by implementing the design pattern Adapter (Gamma et al., 1994), i.e., by developing adapters to specific frameworks. An example of the application of these principles to agro-environmental models is given by the BioMA (Biophysical Model Applications; http://bioma.jrc.ec.europa.eu/index.htm; Donatelli et al., 2012) platform of the European Commission, where the focus is moved from the framework to multi-approach, extensible components for the simulation of processes within different sub-domains (e.g., crop growth and development, soil hydrology, plant-pathogen interactions).

Reimplementation and reuse of the Canegro model from sugarcane to giant reed

This paper presents a component-based reimplementation of the sugarcane model Canegro (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002; Singels et al., 2005); in particular, the version of the model we started from is the one implemented in the DSSAT suite (Jones et al., 2003; Jones et al., 2008). UNIMI.Canegro was here re-built as a framework-independent .NET 3.5 software library, characterized by a fine level of granularity. Each simulated process (e.g., photosynthesis) is made up of independent basic units (e.g., light interception, carbon fixation, maintenance and growth respirations) which can be easily substituted by alternative approaches. The main advantages of this kind of re-implementation lie (i) in the possibility of sharing knowledge via ready-to-use software units, because of the fine granularity and of the absence of dependencies, and (ii) in the ease of reuse and extension of the component algorithms. The latter is here demonstrated with the extension of the component to the simulation of giant reed (*Arundo donax* L.), a promising energy crop (Mariani et al., 2010; Pilu et al., 2012) sharing several morphological and physiological traits with sugarcane.

2.3. Canegro reimplementation

2.3.1. Software architecture

The software design follows the guidelines outlined by Donatelli and Rizzoli (2008), thus promoting component reusability by limiting dependencies and providing a semantically rich, public interface (i.e., IStrategyCanegro). According to the design pattern façade, this interface is implemented by all the simple and composite model units included in the UNIMI.Canegro component (i.e., a strategy). More specifically, a simple strategy is an indivisible unit of algorithm coherently representing a sub-process, i.e., the smallest piece of algorithms for which alternate approaches exist or could exist in the future (Figure 1). Simple strategies are composed into objects of increasing complexity, that – according to the composite pattern – are in turn subject to composition, leading to a hierarchical structure culminating with a composite strategy that represent the whole model (Figure 1). This architecture allows the extension of the component by simply adding new strategies implementing original or existing modelling approaches to reproduce the process of interest. The implementation of the bridge pattern implies the separation of model algorithms from data-types structures (i.e., domain classes, that can be extended independently) in two different components (Donatelli and Rizzoli, 2008). This pattern allows the substitution of modeling approaches – that are non-unique by definition – without changing the interfacing between I/O services and domain description, that does not vary according to the modelling approach used. The domain classes describe the biophysical domain by including inputs and outputs of the model with their attributes, whereas the ontology of the parameters, related to the specific modeling representation and not to the domain, is made available via the related strategies. The coherence of input, output and parameter values with their ontology can be verified through the test of pre- and post-conditions, according to the design-by-contract approach (Meyer, 1997). UNIMI.Canegro, currently used for sugarcane simulations within the BioMA platform, is distributed in a Software Development Kit including hypertext files documenting the code, the implemented approaches, the software design and the code (Visual Studio 2010) of a sample application illustrating how to use it. Strategies, domain classes and interfaces can be inspected via an external application named Model Component Explorer (http://agsys.cra-cin.it/Tools/MCE/help/). UNIMI.Canegro can be coupled to other available .NET framework-independent components for the simulation of, e.g., soil water balance (http://agsys.cra-cin.it/tools/soilw/help/) or plant-pathogen interactions (http://agsys.cra-cin.it/tools/diseases/help/).

2.3.2. Component outputs consistency with DSSAT-Canegro

The new version of Canegro was evaluated by comparing its outputs with those produced by DSSAT v4.5 (http://dssat.net/downloads/dssat-v45). In order to isolate the differences due to the implementation of the plant growth algorithms from those generated by the simulation of water balance, (i) a fully irrigated treatment was chosen for DSSAT (Pongola site, 1968-1971, included in the DSSAT setup; parameters were set to the default values for the variety NCo376; Jones et al., 2008), whereas (ii) UNIMI.Canegro was run under potential conditions. Figure 2 and Table 1 demonstrate that the two versions exhibit a good agreement, with values of the accuracy metrics close to their optima. The slight differences in stalk biomass, sucrose content, and plant height (Figs. 2.a, 2.b, 2.c) simulated by the two versions are explained by short periods of water stress simulated by DSSAT starting from DOY 232 that were not reproduced by the UNIMI version of the model (run under non-limiting conditions for water). The number of leaves on the primary tiller (Fig. 2d) and the tiller density (Table 1) are DSSAT outputs indirectly showing the dynamics related with the cohorts of shoots, a distinctive feature of Canegro. The latter is responsible for total leaf area index (LAI) and green leaf area index (GLAI), which were slightly overestimated in the component version as highlighted by the negative value of coefficients of residual mass. However, these differences did not markedly affect canopy light interception, as well as biomass and sucrose accumulation, thus leading to consider the new version of Canegro as a reliable reimplementation of the original one.

2.4. Model reuse: from Canegro to Arungro

The interest in giant reed as energy crop has increased only recently and this is probably the reason why crop models for simulating this species are not available. Moreover, the peculiar features of giant reed makes generic crop simulators (e.g., CropSyst, WOFOST, STICS) unsuitable and attempts targeting the calibration of their parameters would likely lead to poor performance and to inconsistent calibrations, potentially undermining model robustness (Confalonieri et al., 2010). The Canegro model – in its component version – was used as a starting point for the definition of a new, explanatory giant reed model (Arungro, hereafter). This choice is suggested by the affinity of giant reed to sugarcane, since the two species share many of the traits distinguishing them from most of the herbaceous crops (e.g., presence of a rhizome and its role in determining the rate of stalk emission). Canegro is detailed in the description of these peculiar processes, that can be modulated via dedicated parameterizations to properly reproduce giant reed behavior. For the processes where the differences between the two species required the formalization of new algorithms, the extensibility of UNIMI.Canegro simplified the modification of specific modelling approaches via the addition of alternative strategies. An example for this refers to the way LAI and GLAI are simulated: observations, indeed, revealed differences between the two species, mainly related with the different dynamics of leaf development and senescence. For this aspects, the peculiar giant reed features were thus considered by developing two new strategies for substituting two of those composed in the UNIMI.Canegro strategy LeafAreaIndexC (see Figure 1), thus keeping most of the Canegro strategy unchanged. Moreover, the software architecture favored the revision of some of the Canegro strategies involved in biomass partitioning and maintenance respiration, allowing also the inclusion of the effect of rhizome biomass on tiller population at spring restart. Accounting for all the modified strategies, the extended version of the component (i.e., UNIMI.Arungro) shares with UNIMI.Canegro about 70% of the strategies. The results of a sample simulation (shown in Fig. 3) where Arungro outputs were compared with the measured data collected by Ceotto et al. (2013) confirm the potentialities of the new giant reed model and provide a proof-of-concepts of the usefulness of enhancing reusability in the agro-environmental model design.

2.5. Conclusions and remarks

The international community recognizes the usefulness of software design favoring model reuse. However, most of the agro-ecological models are still implemented in monolithic software units using outdated software designs and technologies. This is far from limiting the problem to a programming issue, since the use of unsuitable technology for developing complex, integrated system models is likely one of the major factor limiting the formalization of new knowledge in mathematical constructs. The result is a gap between scientific knowledge and its formalization into simulation models. The reimplementation of Canegro presented in this paper is aimed at providing third parties with a version of the model explicitly designed for being easily used, composed and extended, regardless of the simulation environment. The reusability of the component was here demonstrated via the development of the first giant reed crop model, derived by extending the original model for sugarcane.

Acknowledgements

Dr. Matthew Robert Jones and Dr. Maurits van den Berg are gratefully acknowledged for their precious personal communications.

Table 1. Agreement metrics between some of the main variables simulated by the original DSSAT version of Canegro and the corresponding ones simulated by the version of the model re-implemented in this study: Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970, NSE; −∞ to 1; optimum 1), coefficient of residual mass (CRM; −∞ to +∞, optimum 0), and coefficient of determination (R^2; −∞ to +∞, optimum 1).

Variable	NSE	CRM	R^2
thermal time for emergence (°Cd)	1.00	0.00	1.00
thermal time for tiller development (°Cd)	1.00	0.00	1.00
tiller density (m^{-2})	0.93	-0.03	0.95
number of leaves on the primary tiller	1.00	0.01	1.00
LAI (m^2 m^{-2})	0.96	-0.09	0.99
GLAI (m^2 m^{-2})	0.95	-0.01	0.95
light interception (%)	0.99	0.01	1.00
aboveground biomass (t ha^{-1})	1.00	0.03	1.00
stalk dry mass (t ha^{-1})	1.00	0.01	1.00
stalk sucrose mass (t ha^{-1})	1.00	0.02	1.00
stalk height (m)	0.99	-0.02	1.00

Figure 1. Strategy diagram of the Canegro component. The new strategies created to extend the Canegro model for the simulation of giant reed (leading to the model Arungro) are highlighted.

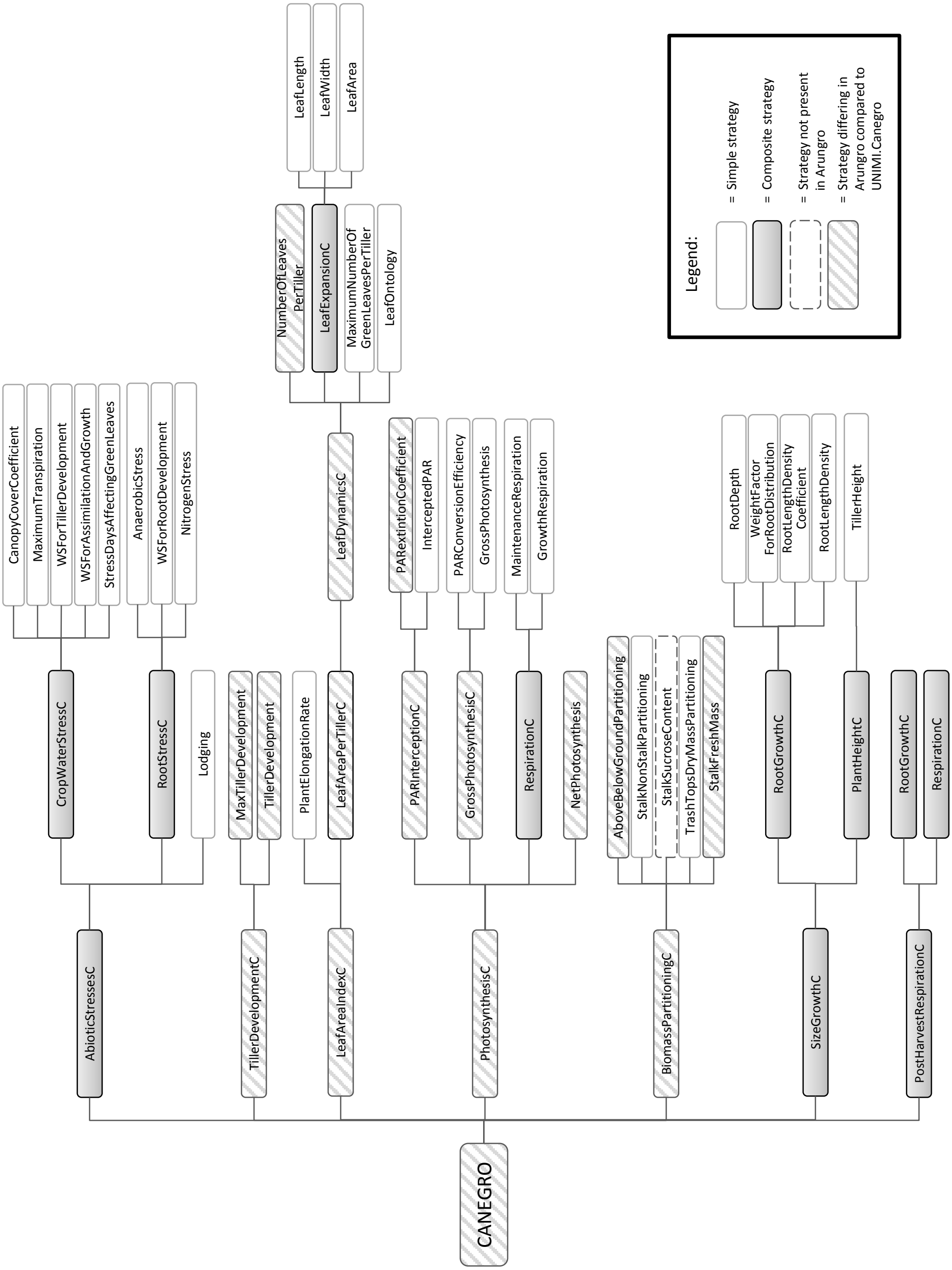


Figure 2. Comparison of relevant outputs simulated by the original DSSAT version (thick line) and by our component-based reimplementation (dotted line): (a) stalk dry mass (t ha^{-1}), (b) stalk sucrose content (t ha^{-1}), (c) stalk height (m), and (d) total number of leaves on the primary tiller.

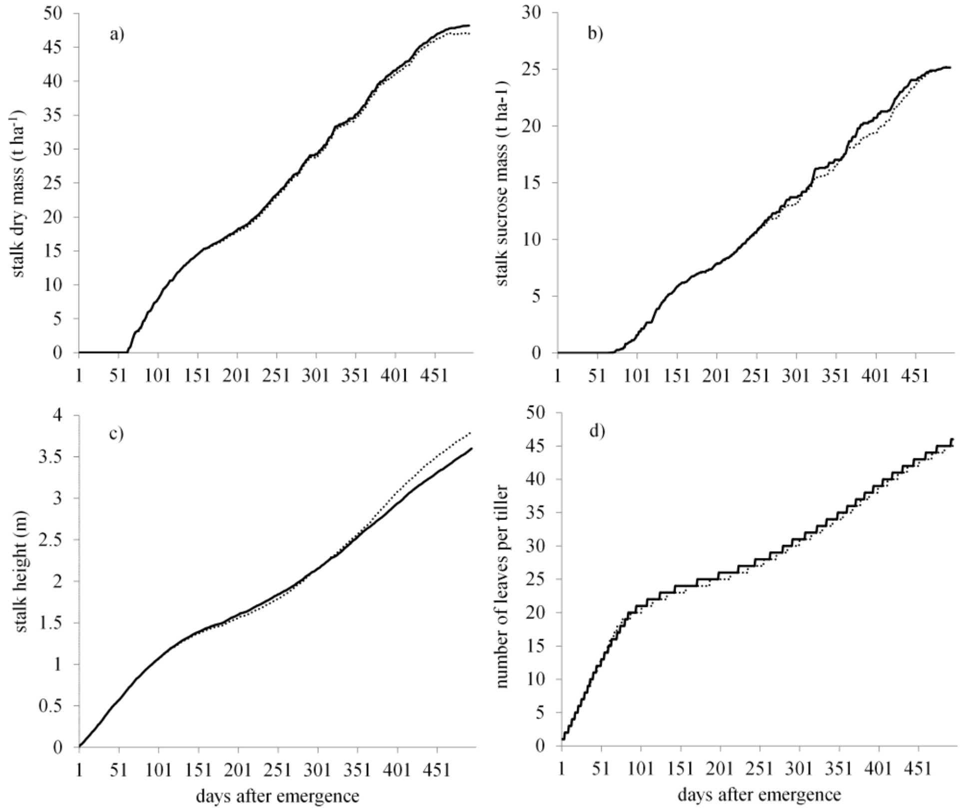
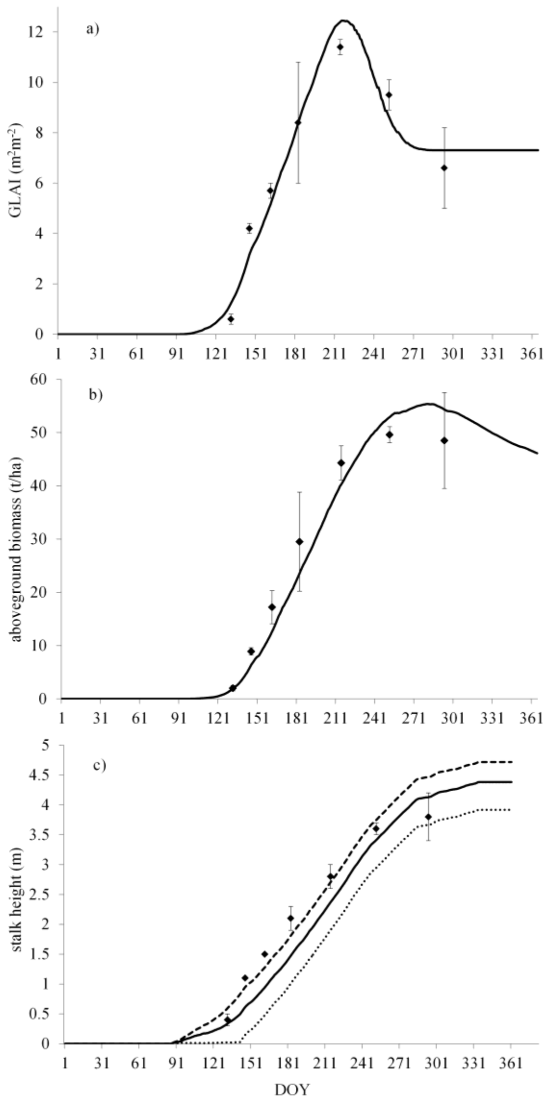


Figure 3. Comparison between outputs of Arungro and giant reed data measured by Ceotto et. al (2013): (a) GLAI (m^2 m^{-2}); (b) aboveground biomass (t ha^{-1}); (c) height of the primary stalk (dashed line), the youngest tiller (dotted line), and mean canopy height (thick line) (m). Error bars represent standard deviation of observations.



ARUNGRO: GIANT REED GROWTH AND PRODUCTIVITY MODEL

Caterina Francone, Sevim Seda Yamaç, Tommaso Stella, Enrico Ceotto, Valentina Pagani, Roberto Salvatore Pilu, Roberto Confalonieri

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3.1. Abstract

In recent years giant reed (Arundo donax L.) has become an important player in the bioenergy industry. This sector raised interest in its cultivation since giant reed (i) unfits for human and animal consumption, and (ii) showed high biomass yields with low input requirements. Therefore, this crop can occupy –in theory– marginal areas, and be efficient from the economic and energetic point of view without competing for land surfaces with food crops. Crop models are tools able to evaluate the potentialities of this emerging energy crop in different areas and scenarios, useful to identify where it can be advantageous to convert land to giant reed cultivation. However, due to the peculiar traits of giant reed, generic crop models fail to reproduce and predict growth dynamics of this species, underlining the need of a species-specific model. In order to fill this gap, this work proposes a model for giant reed growth and development suitable for multi-year simulations, implemented as an extension of the sugarcane model Canegro. The choice of a sugarcane model as a starting point for the definition of a giant reed model (i.e., Arungro) is supported by the similarity of the two species, which share several morphological and physiological features. The calibration and evaluation of Arungro were performed with datasets collected during specific field experiments carried out in Northern Italy between 2009 and 2012. The dynamics of leaf area index, aboveground biomass, and stem height were monitored for a variety of crop ages and management conditions. Simulations resulted satisfactory, with average RRMSE, modelling efficiency and coefficient of residual mass for aboveground biomass of 39.72%, 0.48 and -0.19 with calibration datasets and 29.58%, 0.63, and 0.11 with evaluation datasets, respectively. To the author’s knowledge, this is the first growth and development model specific for giant reed. Moreover, the features of reusability and extendibility of the model make Arungro suitable for collecting future improvements in the model description of giant reed, achieved through the in-depth analysis of the specific processes of this plant.

Keywords: *Arundo donax* L., giant reed, crop model, aboveground biomass, Arungro.

3.2. Introduction

World population is expected to grow rapidly in the next 50 years together with living standards, setting an open challenge to meet the consequently increased global energy demand.The objective of the satisfaction of 80% of this demand with renewable energy sources in 2050 (IPCC, 2011). Requires a continuous update in policies for bioenergy and biofuels. The potential contribution of biofuels to energy security actually remains matter of discussion, as well as their impact on food prices, on climate-change mitigation and also on agricultural development (FAO, 2008). However, according to the International Energy Agency, the 27% of the world transport will be dependent from biofuels by 2050 (Technology Roadmap: Biofuels for Transport, IEA 2011; URL: http://www.iea.org). Currently, ethanol represents the 85% of the world production of liquid biofuel (FAO, 2008). Among the main bioenergy crops (e.g., sugarcane, maize, switchgrass) giant reed (Arundo donax L.) is emerging as a source of biomass both for second generation bioethanol (i.e., lignocellulosic ethanol) and for combustion heat production (Pilu et al., 2012; Pompeiano et al., 2013). Comparative studies reported that bioethanol yield per hectare can be higher for giant reed than for maize and switchgrass (Williams et al., 2008). Giant reed is a tall and fast growing perennial reed likely diffused in South-Eastern Asia, North Africa and Southern Europe for thousands of years, and later naturalized in warm temperate Mediterranean areas (Lewandowski et al., 2003; Mariani et al., 2010). When properly managed, a giant reed stand can last even 20-30 years (Ceotto et al. 2013); after each harvest (normally one per year), the crop re-sprouts from the rhizome. Thanks to the huge development of this organ in the subsoil, the species tolerates different types of soils (Perdue, 1958) and achieves good results in terms of biomass yield even under low agronomic inputs (Christou et al., 2000; Williams et al., 2009). Despite the C3 photosynthetic cycle, giant reed exhibits growth rates similar to those measured in C4 crops (Cosentino et al., 2006), producing up to 50 t ha^{-1} of aboveground biomass at harvest

(Angelini et al., 2009; Ceotto et al., 2009). The propagation is agamic (e.g., via rhizome extension, flood dispersal of rhizome and culm fragments) due to its sterility traits (Angelini et al., 2009).

Simulation models of agricultural systems help to assess the environmental influence of converting land to biofuel crops and their potential productivity (Thomson et al., 2009). At the same time, whole information about energy crop management practices and critical data for model development is still lacking (Surendran Nair et al., 2012). However, giant reed appears as a suitable candidate for the development of a growth and productivity model: its low genetic variability (Mariani et al., 2010) (i) excludes in theory the possibility of including in the model cultivar-specific processes, and (ii) allows to identify a single set of parameters to describe the crop worldwide. Despite a structural model (L-DONAX, Thornby et al., 2007) and some relationships for phenological (Graziani and Steinmaus 2009; Spencer and Ksander, 2009) and biometric (Pompeiano et al., 2013) variables retrieved from field experiments were proposed, no specific crop model has been so far developed for giant reed.

In this study a process-based model (i.e., Arungro) for simulating giant reed growth and development is proposed and evaluated against different datasets collected in Northern Italy. Arungro was developed by extending the recently proposed UNIMI.Crop.Canegro component (Stella et al., 2014), which implements the DSSAT 4.5 version of the sugarcane model Canegro (Jones et al., 2008). The reason for this choice was twofold, namely (i) the possibility to reuse part of a detailed model of a crop sharing common features with giant reed, and (ii) the benefit of inheriting a component-oriented, framework-independent architecture which enhances the potentiality of use and development by third parties. Moreover, this technology is the same used by the European Commission for the simulation of the agro-environmental models within the BioMA platform (Biophysical Model Applications; http://bioma.jrc.ec.europa.eu/index.htm). The newly developed model was calibrated and evaluated via dedicated datasets exploring a reasonably wide range of the crop variability under different climatic and management conditions.

3.3. Materials and methods

3.3.1. Models description

The proposed UNIMI.Crop.Arungro model re-uses about 70% of the approaches implemented in the component version of the Canegro model (Jones et al., 2008) recently released by Stella et al.(2014). This choice derived from the similarity of some morpo-physiological traits between the two crops (e.g., the role of the rhizome in the determination of tiller density). Both the models implement a detailed description of the dynamics of leaf area index (LAI) at the tiller and leaf level, accounting for leaf size heterogeneity on a single tiller and among different tiller cohorts. Biomass accumulation follows a radiation use efficiency approach which converts daily intercepted radiation to gross photosynthesis. The latter is turned into net photosynthesis by subtracting growth and maintenance respirations. Figure 1 depicts the model diagram, highlighting the strategies (i.e., the smallest unit of the algorithm coherently representing a sub-process) that were newly developed in this work whenever dedicated parameter calibration of the original (i.e., Canegro) approaches was not sufficient or inadequate to reproduce giant reed processes. That is the case, for example, of the algorithmic formalization of the dynamics of the tiller population. Canegro allows the tiller population to grow (i.e., new tillers are emitted) up to a peak in correspondence with a predetermined stage of crop development, when the model forces the younger tillers to die and tiller population to decrease. This dynamic is not coherent with the one observed in giant reed fields, with no data supporting adecrease in population. The strategy describing the evolution of tiller population was therefore substituted in Arungro with an approach which leads the number of tillers to a plateau when a maximum number of tillers are reached. Another discrepancy between the two models lies in the description of the processes leading to green and total LAI estimation. To one side, in Canegro leaves continue to emerge on the tillers in order to reproduce an indeterminate growth, whereas Arungro simulates giant reed tillers with a determined maximum number of leaves. This solution, together with the different management of leaves senescence between the two models, explains the different pattern of evolution of the leaf area (Figure 2). While emitting new leaves on a tiller, the sugarcane model makes some of the oldest leaves die, in order to keep the number of living leaves under a certain threshold. In this way, from the beginning of leaf senescence, simulated sugarcane green LAI and total LAI diverge, with the latter continuously increasing. With giant reed, and therefore in Arungro, the situation is different: only few of the oldest leaves are forced to death (on thermal time basis), leading to a steep reduction of the green LAI in proximity to harvest, when the total LAI maintains a constant value. Light interception (function of LAI) is modeled with the same approach in both Canegro and Arungro (i.e., Lambert-Beer equation), although for the latter the extinction coefficient was kept at a constant value (0.29) as measured during a whole season by Ceotto et al. (2013).

The perennial nature of giant reed rhizome originates the necessity to perform multi-year simulations. With the aim of better reproducingthe crop behavior all along the life time of the crop, some modifications were introduced in the model. Starting from the establishment year, the maximum stem emission rate was modulated as a function of the root biomass, used as a proxy of rhizome resources:

$$StemDensity_{\max} = \mathrm{MaxTillerPop}\left[\left(\frac{RB - RB_b}{RB_{opt} - RB_b}\right) \cdot \left(\frac{RB_{\max} - RB}{RB_{\max} - RB_{opt}}\right)^{\frac{RB_{\max} - RB_{opt}}{RB_{opt} - RB_b}}\right]^C \quad (1)$$

where MaxTillerPop (maximum tiller population, m-2) is a parameter used in Canegro to shape the stem density increasing rate, RB (t ha-1) is root biomass,RBb(t ha-1), RBopt (t ha-1) and RBmax (t ha-1) are minimum , optimum and maximum root biomass, respectively. C is an empiric parameter. As well as the tiller population dynamics, also the partitioning of maintenance respiration needed a revision in order to make multi-year simulation feasible. In Canegro, this respiration lies on the daily assimilation, producing an unrealistic slump in the early stages of crop growth after re-sprouting. During this period, the huge root biomass formed before harvest is responsible of high respiration rates, which reset the growth of aboveground organs to zero. For this reason, Canegro multi-year simulations usually do not use pre-harvest root biomass values for the initialization of the post-harvest simulations (van den Berg, personal communication). In Arungro, root maintenance respiration depletes only root (and therefore, rhizome) provisions, reducing root biomass without affecting tillers growth. In this way, multi-year simulations can be run without the need of breaking any state variable of the model.

3.3.2. Model calibration and evaluation

The calibration of the Arungro model was based on the Canegro parameters default values (Jones et al., 2008), and further enhanced by the collection of specific observations of giant reed stands under different climatic and management conditions. The two experimental sites are located in the alluvial plain of the Po Valley (Northern Italy) characterized by mild continental and humid subtropical climates. The first experiment was carried out between 2009 and 2011 at the Experimental Station of the Italian Agricultural Research Council (CRA), located in Anzola (Lat. 44° 32'N, Long 11° 11'E, 38m a.s.l) and described by Ceotto et al. (2013). Giant reed was planted in March 2007 using a local clone with rhizome spacing of 0.6 x 0.6 m. The crop was fertilized every year and no irrigation was applied during the growing seasons. The second experiment was carried out in 2013 at the Experimental Farm of the University of Milan, in Landriano (Lat. 45° 18'N, Long 9° 15'E, 88m a.s.l.). The mean 2013 maximum and minimum temperature of the area were 19°C and 9°C respectively, and the cumulated rainfall was about 1000 mm year^{-1}. The crop planting density was 2 x 2 m. The area of the giant reed stand was divided in three plots, each one established in a different year, starting from 2010 until 2012. This design allowed to contemporary monitor three ages of *A.donax*. For model development the measurements of the first-year plot were excluded, since the behavior of the crop is known to deviate in the first cycle compared to the following ones (Angelini et al., 2009). No irrigation and fertilizer were applied during the growing season. At each sampling date, 10 stems were randomly collected from each plot for the measurement of the following variables: number and dimensions (i.e., length and width) of leaves on each stem, density and height of stems, and aboveground dry biomass. The sampling size was determined by applying the visual Jackknife resampling method (Confalonieri et al., 2007) to the first sampling observations.LAI was estimated with the PocketLAI smartphone app in three points randomly selected in each plot (Francone et al., 2014). The fresh biomass was gradually oven-dried at 75°C and 105 °C until constant weight was reached.

Table 1 shows the datasets split for the calibration and evaluation simulations, considering each Anzola and Landriano experiment as independent. This choice was recommended because of (i) the shortage of inter-seasonal dataset available in the literature, and (ii) the risk to perform a calibration including a local effect due to the differences between the environmentalconditions of the two sites (). The contemporary presence of different crop ages in Landriano plots was relevant for the characterization of crop behavior during re-sprouting, when the rate of stem emission is likely related to resources availability in the rhizomes and directly influences stem population dynamics. The UNIMI.Crop.Arungro component was run considering crop growth not limited by water or nutrient shortage. Meteorological inputs for Anzola and Landriano simulations were retrieved from a gauge station next to the field and the regional database by ARPA Lombardia, respectively. Parameters whose values represent morphological characteristics of the plant (e.g., maximum leaf length, maximum leaf width) were set accordingly to measured values (Table 2). If no information about their values was retrievable from direct measurements, parameters were tuned via trial and error procedures in order to fit observed trends of the main synthetic variables (e.g., AGB, plant height).

The agreement between observed and simulated values was evaluated by using the relative root mean squared error (RRMSE, minimum and optimum = 0%; maximum + ∞), the modeling efficiency (EF, -∞ ÷ 1, optimum =1, if positive, indicates that the model is a better predictor than the average of measured values;Nash and Sutcliffe, 1970), the coefficient of residual mass (CRM, 0-1, optimum = 0, if positive indicates model underestimation) and the parameters of the linear regression equation between observed and predicted values.

3.4. Results and Discussion

3.4.1. Calibration

Information about model parametersand source of determination is shown in Table 2. Although the literature about the crucial variables needed by the model was poor, values describing development progress and leaf characteristics are in the range of those proposed elsewhere. Base temperature for sprouting is coherent with what reported by Spencer and Ksander (2006). The maximum number of leaves value was consistent with the studyof Giessow et al. (2011) and the one by Spencer et al. (2005) who observed values between 24 and 29. The calibrated values of the maximum leaf width, length and area are in line with the results found by Giessow et al. (2011) during a multi-year monitoring on a large area in California.

The agreement between observed and simulated values after calibration is shown Figure 2 and Table 3. The overall accordance was reasonably good for biomass assimilation and stem growth estimations mainly in the first part of the variability domains. RRMSE metrics ranged from 20% to 59% and 21% to 25% for organ biomasses and stem height, respectively. The variability of the observed plant features, stressed by error bar magnitudes, underlined the high degree of heterogeneity characterizing the crop. Moreover, the decidedly different planting density used for Landriano (i.e., 0.3 rhizomes m^{-2} against a value of 2.8 for Anzola) tends to strengthen the variability of the samples, due to the clear edge effect characterizing the plots. Modeling efficiencies are close to optimum for Landriano_3y aboveground biomass and Anzola stem height, whereas the best coefficient of residual mass score (i.e., -0.09) was obtained for leaf biomass in Anzola. A marked deviation from observations was shown forLAI (Figure 2a), in particular for both Landriano datasets where a pronounced overestimation by the model is provenby the negative values of the coefficient of residual mass. This discrepancy can be partly explained by the difference between the LAI measurement methods used in the two sites (i.e., destructive in Anzola and gap fraction-based in Landriano). The maximum measurable LAI values by camera devices are generally lower than the direct ones, since a gap fraction saturation effect is typical for close canopy conditions (Gower et al., 1999; Francone et al., 2014). This fact partly explains the not satisfactory parameters of the linear regression between simulated and measured LAI in Landriano. With this exception, those parameters are satisfactory with slope values close to one for all simulations. In most cases R^2 is larger than 0.94, with Anzola stem height best performing as highlighted by its intercept value.

3.4.2. Validation

Figure 3 shows the performance of the calibrated model with evaluation datasets. Compared with calibration, a general improvement of model estimations was observed in the second part of the range of variability (Figure 2). Consistently, the agreement metrics highlighted better performances for LAI, aboveground and stem biomasses (Table 3).In particular the modeling efficiencies for these state variables ranged from 0.75 to 0.9 for both Anzola datasets. LAI evaluation in Landriano, as observed with calibration datasets, appears consistently underestimated. Moreover in this site the coefficient of variation (i.e., the ratio of standard deviation to the mean) reached maximum value above 40% for aboveground biomass thus dampening the model underestimation. The coefficients of residual mass confirmed this trend for both aboveground biomass and stem height with values of 0.40 and 0.32, respectively. Evaluation highlighted the necessity of improving the simulation of stem height, which reached RRMSE values above 32% in all sites. However, this variable is completely has no effect in the estimation of LAI or photosynthesis, and therefore its wrong estimation would not produce errors in the forecasting of giant reed productivity. The aboveground biomass RRMSE values effectively ranged from 18.17% in Anzola to about 41% in Landriano. This variable is the key one in view of bioenergy application, and it was accurately simulated by Arungro, as highlighted by the performance indices very close to the ones obtained for other well-known crops (e.g., Confalonieri et. al, 2009; Brisson et al., 2002).

3.5. Conclusions

The Arungro model for giant reed growth and development is here presented as an extension of the sugarcane Canegro model. The proposed Arungro model included new approaches aiming at reproducing some peculiar aspects of giant reed stands, in order to provide a robust support tool for evaluating the emerging giant reed agro-environment. In light of the moderate availability of literature and agronomic information on the crop behavior, to two dedicated field campaigns in Northern Italy were set to develop and evaluate the model. The differences among the two experimental sites allowed to investigate the response of the crop to a variety of meteorological and management conditions, the latter decidedly differing for the initial planting densities. Model performances resulted reasonably satisfactory, in particular when comparing measured and simulated aboveground biomass. The results are encouraging, especially considering the low availability of agronomic literature characterizing the crop, and the novelty represented by the model in itself. The inter-season specific monitoring of additional crop characteristics (e.g., stem and leaf morphology) were essential in supporting model development and the calibration process.

The weak genetic variability of thespecies suggests the identification of a single set of crop parameters, likely valid worldwide. This possibility, once tested, should have a great impact in simplifying model use, and possibly extends the community of Arungro users beyond modelers, towards technicians and researchers in the bioenergy branch.

Acknowledgements

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Table 1. Dataset used for calibration (cross) and validation: leaf area index (LAI), aboveground biomass (AGB), stem biomass (SB), leaf biomass (LB), and stem height (SH).

Experiment name.	Location	Year	Crop age	Variables	Used for calibration
Anzola_3y	Anzola	2009	3	LAI, AGB, SB, LB, SH	
Anzola_4y	Anzola	2010	4	LAI, AGB, SB, LB, SH	x
Anzola_5y	Anzola	2011	5	LAI, AGB, SB, LB, SH	
Landriano_2y	Landriano	2013	2	LAI, AGB, SH	x
Landriano_3y	Landriano	2013	3	LAI, AGB, SH	x
Landriano_4y	Landriano	2013	4	LAI, AGB, SH	

Table 2. Parameters values calibrated for Arungro (C: calibrated parameters; L: literature; E: local experience; M: measured; D: Canegro default values).

Parameter name	Description	Value	Units	Determination
TTEmergenceRatoon	Thermal time to emergence for a ratoon crop	125	°Cd	C
TTEmergencePlant	Thermal time to emergence for a plant crop	428	°Cd	D
TTLeafSenes	Thermal time for leaf senescence	1650	°Cd	C
TTStalkElongation	Thermal time after which stalk elongates	1050	°C	D
TTEmergencePeakTillerPop	Thermal time emergence to peak tiller population	600	°Cd	D
TBaseEmergence	Base temperature for emergence	9	°C	L
TBaseLeafEmission*	Base temperature for leaf emission	6	°C	E
TBasePlantExtension*	Base temperature for plant extension	6	°C	E
TBaseStemElongation*	Base temperature for stem elongation	6	°C	E
TBaseTillerDevelopt*	Base temperature for tiller population development	7	°C	E
TBasePhotosynthesis*	Base temperature for photosynthesis	7	°C	D
TBaseRootExtension*	Base temperature for root extension	10	°C	D
LeafAngle	Last expanded leaf insertion angle	25	°	M
MaxNumL	Maximum number of leaves on a tiller	28	unitless	M
MaxNumEL	Maximum number of expanding leaves on a tiller	7	unitless	M
MaxNumGL	Maximum number of green leaves under well water conditions	27	unitless	M
NumSenesLeaves	Number of senescence leaves	10	unitless	M
LNumPlSwitch	Leaf number at which the phyllocron changes	18	unitless	D
LeafIDLeafAreaLimit	Leaf ID above which leaf area is limited	15	unitless	D
MaxRadConEff	Maximum radiation conversion efficiency	13	g MJ^{-1}	M
MaxLeafAreaCoeff (1,2,3)	Quadratic equation coefficients for maximum leaf area	0, 0, 180	cm^2	C, L
MaxLeafLengthCoeff (1,2,3)	Quadratic equation coefficients for maximum leaf length	0,0,65	cm	C, M
MaxLeafWidthCoeff (1,2,3)	Quadratic equation coefficients for maximum leaf width	0,0,60	mm	C, M
PartitFractHighTemp	Fraction of aerial dry mass partitioned to stem at high temperature	0.84	t t^{-1}	C
PIAboveSwitchNum	Phyllocron interval 2	90	°Cd	C
PIBelowSwitchNum	Phyllocron interval 1	40	°Cd	C
FractPlantStemElong	Fraction of plant elongation attributable to stem elongation	0.45	unitless	C
UnstressedExtenRate	Unstressed plant extension rate	0.18	mm $°C^{-1}$ h^{-1}	C
MaxTillerPop	Maximum tiller population	35	m^{-2}	E, M
RootBiomassOpt	Optimum root biomass for maximum tiller density	10	t ha^{-1}	C
RootBiomassMax	Maximum root biomass for maximum tiller density	20	t ha^{-1}	C
RootBiomassBase	Minimum root biomass for maximum tiller density	0	t ha^{-1}	C
FracGrossPhotoLostGrowth	Fraction of gross photosynthesis lost for growth respiration	0.242	unitless	D
MaxPartitFractAGB	Maximum partition fraction to aerial dry mass	0.88	t t^{-1}	D
MinPartitFractAGB	Minimum partition fraction to aerial dry mass	0.05	t t^{-1}	D
MinRootLengthDensity	Minimum Root Length Density	0.02	cm cm^{-3}	D
MaxRootLengthDensity	Maximum root length density	5	cm cm^{-3}	D
RootDepthIncreaseGDD	Root depth increase per growing degree day	0.22	cm $(°Cd)^{-1}$	D
RootLengthDenExtinCoeff	Root Length Density Extinction Coefficient by depth	-0.01	cm^{-1}	D
OptTPartitToStem	Temperature below which partitioning of aerial dry mass to stem is equal to 1	9	°C	D
PartitCoeff	Partitioning coefficient for aerial dry mass	0.6	unitless	D
Q10MainteResp	Fractional increase in respiration rate per 10°C rise in temperature	1.68	unitless	D
RefMainteResp	Value of maintenance respiration at 10°C	0.0033871	t t^{-1} d^{-1}	D

*the corresponding value for cutoff temperature is 30 °C.

Table 3. Indices of agreement between observed and simulated aboveground biomass (AGB; t ha^{-1}), leaf area index (LAI; m^2 m^{-2}), stem height (SH; m), stem biomass (SB; t ha^{-1}), and leaf biomass (LB; t ha^{-1}).

Experiment name		Variable	RRMSE	EF	CRM	Slope	Intercept	R^2
Anzola_4y	Calibration	LAI	24.58	0.68	-0.19	1.15	0.28	0.92
Landriano_2y		LAI	88.69	−7.60	-0.74	2.75	−4.79	0.85
Landriano_3y		LAI	88.31	−11.68	−0.73	2.28	−1.97	0.88
Anzola_4y		AGB	40.22	0.47	−0.27	1.39	−3.27	0.94
Landriano_2y		AGB	59.17	0.10	−0.44	1.54	−1.74	0.96
Landriano_3y		AGB	19.77	0.88	0.14	0.94	−2.68	0.94
Anzola_4y		SB	37.05	0.57	−0.23	1.37	−3.00	0.94
Anzola_4y		LB	29.37	0.60	−0.09	1.10	−0.03	0.77
Anzola_4y		SH	21.21	0.83	−0.15	1.20	−0.12	0.97
Landriano_2y		SH	21.60	0.46	0.16	1.37	−1.45	0.95
Landriano_3y		SH	25.40	0.28	0.23	1.24	−1.41	0.97
Anzola_3y	Validation	LAI	19.56	0.85	−0.10	1.15	−0.37	0.93
Anzola_5y		LAI	20.17	0.75	−0.07	1.30	−1.67	0.93
Landriano_4y		LAI	87.65	−21.08	−0.70	3.66	−9.72	0.92
Anzola_3y		AGB	29.62	0.78	−0.12	1.35	−6.39	0.97
Anzola_5y		AGB	18.17	0.90	0.05	1.20	−8.77	0.97
Landriano_4y		AGB	40.95	0.20	0.40	0.83	−11.00	0.97
Anzola_3y		SB	30.30	0.81	−0.17	1.35	−3.91	0.99
Anzola_5y		SB	15.00	0.95	0.02	1.18	−5.34	0.98
Anzola_3y		LB	40.51	0.25	0.06	0.99	−0.33	0.57
Anzola_5y		LB	31.10	0.47	0.14	1.11	−2.13	0.75
Anzola_3y		SH	34.86	0.59	−0.18	1.47	−0.64	0.96
Anzola_5y		SH	43.78	0.30	−0.27	1.51	−0.48	0.93
Landriano_4y		SH	32.81	−0.47	0.32	1.22	−1.79	0.96

Figure 1. Strategy diagram of the UNIMI.Crop.Arungro component.

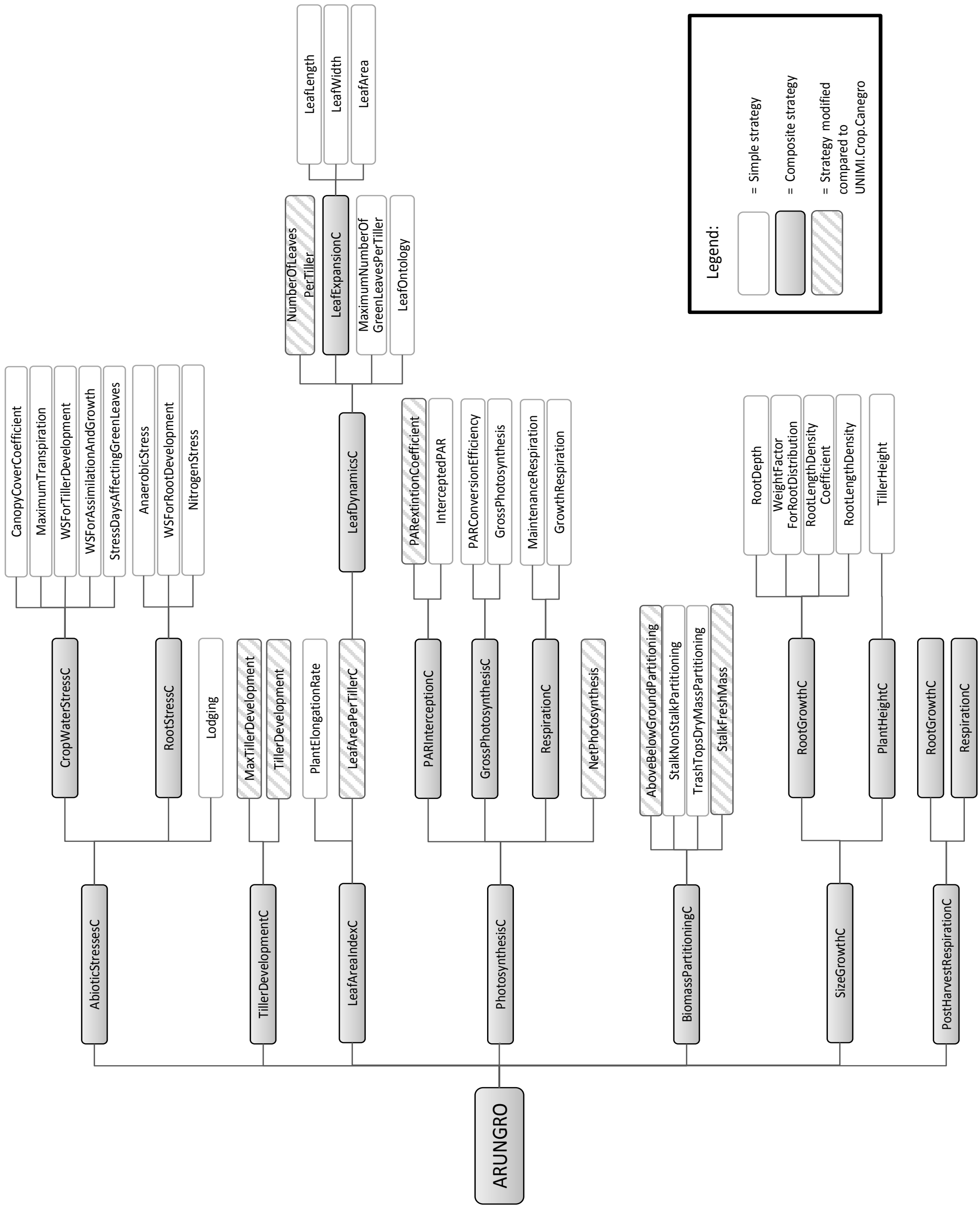


Figure 2. Comparison of the LAI patterns highlighted by Arungro and Canegro, respectively, in two sample simulations: GLAI (green leaf area index) LAI (leaf area index), (a) Arungro and (b) Canegro.

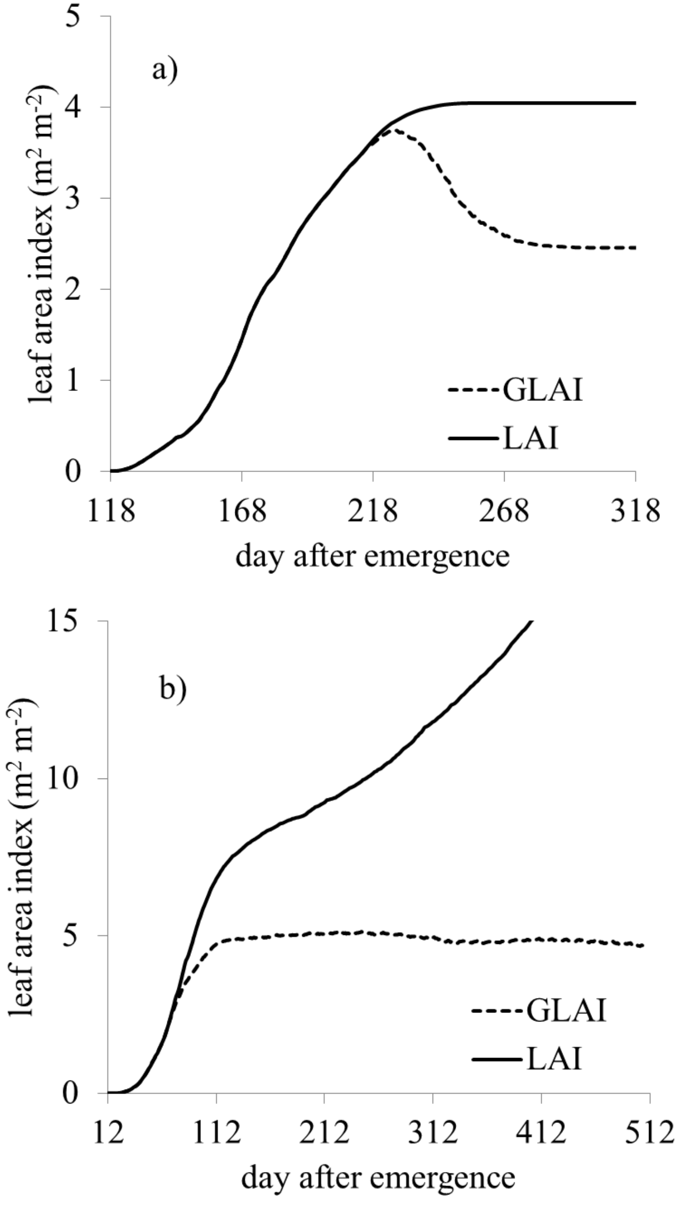


Figure 3. Observed (X-axis) and simulated (Y-axis) leaf area index (LAI), aboveground biomass (AGB), stem biomass (SB), leaf biomass (LB), and stem height (SH) values after calibration. Error bars represent ± one standard deviation.

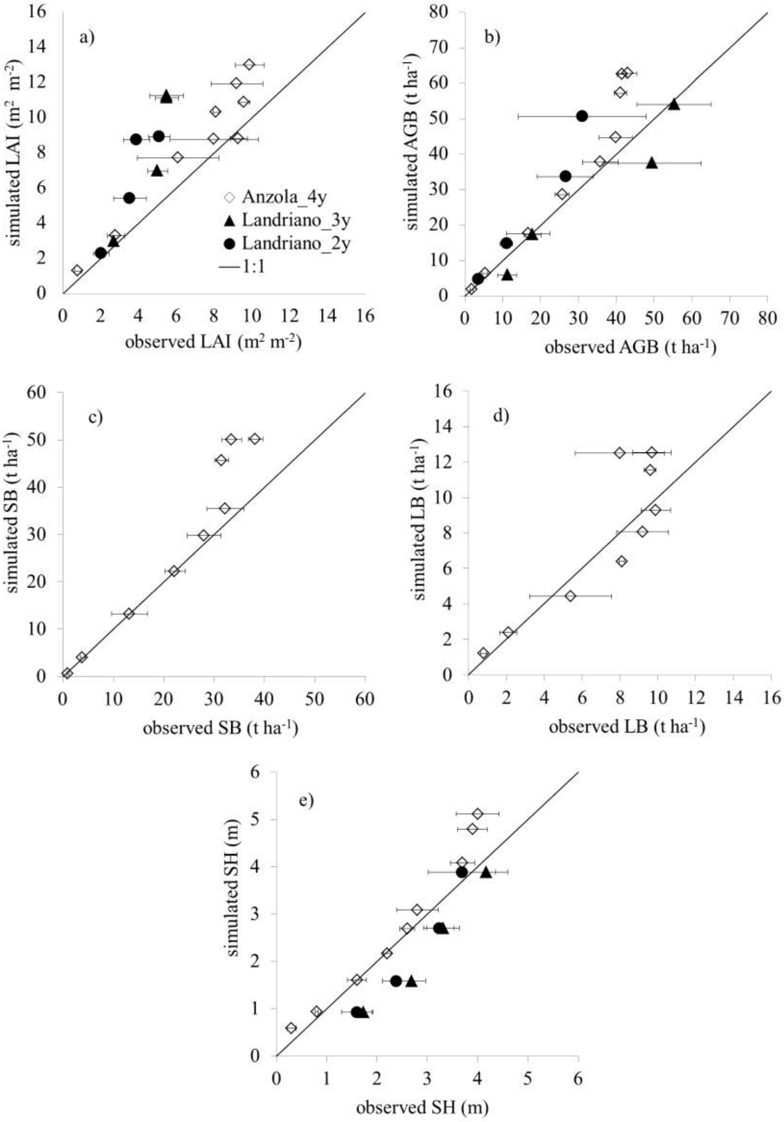
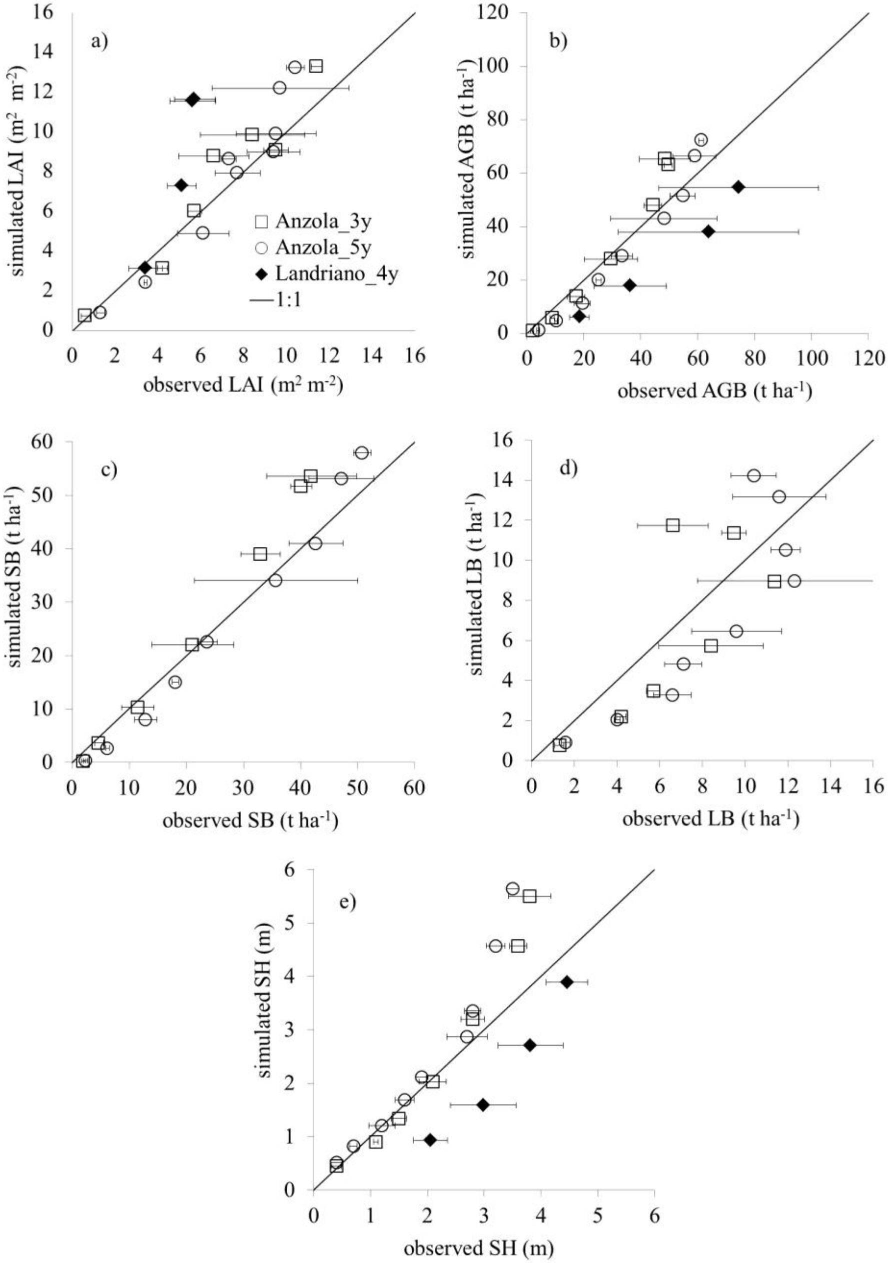


Figure 4. Observed (X-axis) and simulated (Y-axis) leaf area index, aboveground biomass, leaf biomass, stem biomass and stem height values after validation. Error bars represent ±one standard deviation.



ARE ADVANTAGES FROM PARTIAL REPLACEMENT OF CORN WITH ENERGY CROPS UNDERMINED BY CLIMATE CHANGE? A CASE STUDY FOR ARUNDO DONAX IN LOMBARDY (NORTHERN ITALY)

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Are advantages from partial replacement of corn with energy crops undermined by climate change? A case study for Arundo donax in Lombardy (Northern Italy)

4.1. Abstract

Non-food energy crops are increasingly perceived as a promising opportunity to support farmers revenue while reducing the fossil fuel dependency of the agricultural sector and limiting undesired externalities. At EU level, many alternative energy supply chains, technologies and crops have been studied and tested; among the species evaluated, Arundo donax provided the most encouraging results in Mediterranean countries because of the favourable relationship between productivity levels and inputs/cost needed to achieve them. Nevertheless, few resources have been devoted to investigate the response of this crop under climate change scenarios, despite the crucial implications for mid-term planning involving both farmers and policy makers. In this study, we present an exploratory analysis of the climate change impact on giant reed productivity in the Lombardy plain, an intensive maize-based area where corn is expected to be negatively affected by projected changes in thermal and pluviometric regimes. A dedicated simulation environment was developed, by coupling Arungro, a process-based model specific giant reed, to a database including information on land use, full-scale plants distribution, and scenarios for current climate and future projections. Baseline climate (1975-1994) was obtained from the European Commission MARS database, whereas the Hadley3 and NCAR realizations of the IPCC AR4 emission scenarios A1B and B1 were used for 20-year future climate projections centred on 2020 and 2050. Simulations were performed for Agrarian Regions (ARs) selected according to: (i) presence of operating biogas plants,(ii) negative projections for future maize fodder production, and (iii) dairy cattle pressure. These criteria were targeted to maximize potential farmers income while reducing the risk of land use competition between feed and energy crops. Results indicate that an increased suitability of giant reed to the conditions explored in the Region is expected, regardless of the emission scenario, the general circulation model and time frame. The

largest increases in biomass production (+20% in 2020 for all scenarios, and +30% in 2050 for Hadley-A1B) were achieved in the central part of the Region, where the agrofuel sector is already well developed and drive high demand for biomass. Results were less encouraging in the Eastern part of the Lombardy plain, where the crop is already experiencing thermal conditions close to the optimum for this macro thermal species. Results of the present study suggest that the opportunity to adopt giant reed as energy crop could be fruitful even in a medium-long term outlook.

Keywords: Arungro, giant reed, Crop model*, Zea maize* L., renewable energy, biogas plant.

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4.2. Introduction

Climate change is threatening agricultural productions in many areas worldwide, because of raising temperature, unfavourable rainfall distribution and increase in the frequency of extreme weather events. The extent of changes in crop productivity is still an open issue, and its quantification strongly depends on the current level of adaptation of the species in a specific region and on the selected climate change scenario (Porter and Semenov 2005; Lobell and Field, 2007; Masutomi et al., 2009; Semenov and Shewry, 2011; Marin et al., 2012). However, the scientific community is quite concordant in forecasting worldwide yield losses for maize (Jones and Thornton, 2003; Erda et al., 2005; Tatsumi et al., 2011; Fernandes et al., 2012; Supit et al., 2012; Bocchiola et al., 2013), one of the most important food and feed crop. This is also the main crop in the Lombardy region, an area characterized by intensive agriculture and livestock farming situated in Northern Italy. Future projections for maize in this area indicate a decrease in maize productivity due to the effects of climate change on (i) average temperature (IPCC, 1990, 1995, 2007), which will likely shorten the grain filling phase (Supit et al., 2012; Fernandes et al., 2012), and on (ii) water availability (Khang et al., 2009). The influence of climate change on the latter is twofold, referring to rainfall distribution (IPCC, 1995) and to soil moisture storage, because of the increase in evapotranspiration rates. These effects could negatively affect key processes during the crop cycle (e.g., flowering and pollination) undermining the productivity of different crops, including maize, wheat and rice (Confalonieri and Bocchi, 2005; Bianchi, 2005). All the detrimental effects are expected to play a major role under future scenarios, being likely only partially counterbalanced by technological trends.

In this context, the need for analysing the economic and social sustainability of current cropping systems under conditions of no adaptation is emerging rapidly. Maize-based cropping systems will probably experience an increase production costs, given their high request of inputs whose price is constantly increasing (e.g., fuel, fertilizers) and their dependence from irrigation. The importance of water is indeed expected to increase, since raising temperature sand unfavourable rainfall distribution are exacerbating the conflicts between countryside and urban areas during summer months. In this perspective, some farmers are testing alternative business models, with a special focus on the agrofuel sector.

Giant reed (*Arundo donax* L.) is a perennial invasive grass which showed tolerance to a broad spectrum of soil types (Perdue, 1958) and exceptional biomass accumulation rates even with low agronomic inputs (Christou et al., 2000; Williams et al., 2009). These features make giant reed suitable for marginal areas, where the cultivation of other species does not result advantageous. Giant reed, therefore, can be considered as a good solution to the ethical concerns dealing with the competition for land surfaces between food (or feed) and energy crops. The evaluation of the potential productivity of giant reed in Italian environments (e.g., Angelini et al., 2009; Ceotto et al., 2013) indicated the possibility, for giant reed, to achieve higher energetic efficiency compared to maize in terms of attainable energy per hectare (Schievano eta al., 2012). That is the reason why, in Lombardy, different farms involved in energy crops cultivation converted part of their land from maize to giant reed.

The goals of this research were (i) the estimation of climate change impact on giant reed productivity in the Lombardy plain, and (ii) the evaluation of the opportunity of changes in the use of marginal lands from maize to giant reed, by analyzing economic and environmental issues in the medium-long term.

4.3. Materials and Methods

4.3.1. The study area

Lombardy region is one of the more industrialized and intensively cultivated area of Europe, with a gross domestic production (GDP) equal to 21.1% and 2.6% of the Italian and European GDP, respectively. In such a context, agriculture plays a key role in the domestic economy, being characterized by high productivity (GDP/Work unit is 1.3 times that of EU-27) and quality of productions, that contribute for 11.4% to the national agricultural added value. 73% of the regional utilized agricultural area (UUA) is located in the Po plain (720 thousand ha distributed between 44°50’N/8°40’E and 45°50’N/11°80’E), characterized by an overall temperate humid climate and by a pronounced heterogeneity in pedo-climatic conditions (Fumagalli et al., 2011).In lowland,potentially irrigable area account for 695,000 ha (about 95% of plain UAA).The main cropping systems are oriented to cereal and forage production to support the intensive and highly specialized livestock farming of pigs (4,639,142 heads), poultry (19,988,194 heads) and cattle (1,299,449 heads, of which 471,204 are dairy heads). The resulting meat and dairy foodsrepresent about 10% of the 252 national products protected by trademarks, such as Products of Designated Origin (PDO) and Protected Geographical Indication (PGI).Energy crops for first (maize, wheat, sunflower, canola, sorghum)and second generation (mainly wood cut) biofuels cover 4,600 ha. The latters are used – together with five million tons of livestock wastes – to feed the 361biogas plants currently operating in Lombardy (National Institute of Agricultural Economics Research, INEA, 2013). These plants are mainly concentrated in Cremona, Lodi and Brescia provinces, accounting for 137, 68 and 49 plants, respectively, and they are almost entirely characterized by nominal power class up to 1MW (about 96% of total regional plants), corresponding to the maximum threshold allowing to obtain public funding for electricity production from renewable source(Cavinato et al., 2010).Given the strict European regulations for nitrogen loads, the plants also represent a solution to limit the negative externalities from disposal of livestock manures, such as groundwater nitrate pollution (Scaglione et al., 2013).

4.3.2. Definition of the elementary simulation unit and data used for the simulations

Based on the explorative nature of the study, the Agrarian Region (AR) was chosen as elementary simulation unit. ARs results from the aggregations – within each province – of municipalities characterised by homogeneous pedo-climatic conditions and cropping/faming systems structure. In order to identify the ARs of interest, three criteria were used (Fig. 1), based on (i) the presence of operational biogas plants, (ii) future projections of maize fodder production, and (iii) livestock pressure. For the first criterion, we started from the spatial distribution of biogas plants at municipality level (Fig. 1a) to derive the total nominal electric power per AR (Fig. 1b). Results were then used as a proxy to sort AR's depending on theoretical demand for biomass (the greater the total power, the greater the demand).The second criterion made use of unpublished data produced during an official research agreement between the University of Milan and Lombardy Region where the impact of climate change on agriculture in the Region was evaluated, together with adaptation strategies. In particular, the areas where climate change is expected to have the more sever impact on fodder maize were identified (Fig. 1c). The third criterion was aimed at identifying the AR characterized by lowest load of dairy cattle heads, whose diet is characterized by the highest inclusion of maize fodder. Indeed, the partial abandonment of maize crop is supposed to have there a negligible effect on the competition between feed and no-feed crops. For this purpose, the Italian National Institute of Statistics (ISTAT) database was investigated in order to identify the most widespread categories of cattle farming and their own head consistency at Province level. Then, information was downscaled at RA level, by selecting for each category of farm the most representative size (Fig. 1d).

For each criterion, a minimum threshold corresponding to the 50th percentile was calculated and was then used to define a compound filter aimed at reducing the number of total simulation units to be considered. AR were included in the simulation study in case the following conditions were simultaneously satisfied: total installed electric power higher than 2.5 MW; maize yield decrease (compared to the current climate) larger than 12.5%; head of livestock per farm lower than 140. As result, after filtering operation, 16 AR out of 54 were identified as eligible for the study (Fig. 1e).

The European Commission MARS weather database was used to derive the 1975-1994 weather data for the baseline climate. Climate change scenarios were then derived for two contrasting IPCC AR4 emission scenarios, i.e., A1B and B1 (IPCC 2007): the formerrepresents a business as usual scenario (high impact), the latter assuming carbon dioxide stabilization at about 550 ppm already in the short term (low impact). The uncertainty in the projections provided by global circulation models (GCMs)was managed using two different approaches: Hadley3 (Gordon et al., 2000) and NCAR (Collins et al., 2004).Obtained temperature and rainfall anomalies were then used to generate 20 year weather series centred on 2020 and 2050 using a stochastic weather generator (CLIMAK; Danuso 2002).

4.3.3. Model and parameterization

The Arungro model (Francone et al., 2014) used for simulating giant reed calculates biomass accumulation rates based on temperature limited radiation use efficiency approach. The model implements a detailed description of leaf area index dynamics at shoot and plant levels, accounting for leaf size heterogeneity on a single stem and among different stem cohorts. Evolution of stem population is estimated on thermal time basis, with the emission of new stems modulated as a function of rhizome biomass. The model, specifically designed for giant reed, was derived by extending the sugarcane model Canegro (Inman-Bamber, 1991) because of the morphological and physiological features shared by these two species (Stella et al., 2014). Arungro demonstrated its suitability for reproducing giant reed observations collected in dedicated experiments in Northern

Italy (Francone et al., 2014). Once established, giant reed presents a high adaptability to a wide range of soil types, low needs for nutrients, and a marked tolerance to drought because of the deep root apparatus (Pilu et al., 2012). These features allowed – in this exploratory study – to run the Arungro model under potential conditions for water and nutrients.

4.4. Results and Discussion

4.4.1. Future climate scenarios

Figure 2 presents average daily thermal anomalies obtained as difference between climate change scenario and baseline data for all the combinations emission scenario × GCM × time frame. In 2020, the A1B scenarios project higher temperature deviations from the baseline compared to B1 (about 1.7° C versus 1.5 °C), being the latter more heterogeneous according to the GCM used (thermal anomalies range between 0.52 and 1.9°C). Moving to the 2050 time horizon, B1 scenarios tend to be stationary (average temperature increases are stable around 2°C),with increases in thermal anomalies presenting the order NCAR-B1 ~ Hadley-B1<NCAR-A1B <A1B-Hadley.For the latter, temperature increases reach 3.7° ± 0.24°C followinga north-east – south-west gradient. Since NCAR-B1 and Hadley-A1B represent the extremes of temperature range projected, they were selected for the spatially distributed simulations, since allowing to explore the widest range of temperature.

4.4.2. Production levels

For each climate scenario, the variability in the giant reed aboveground biomass values (t ha^{-1} year^{-1}) simulated for all the elementary simulation units is presented in Fig. 3. The yields simulated under future climate projections were always higher than those obtained for the baseline. The latter, however, show a slightly higher variability in the inter quartile range that justifies the absence of outliers. For the 2020 time horizon, average simulated yields were around 57 t ha^{-1} for both the climate scenarios, with the differences among years and ARs overcoming those due to the considered GCM and emission scenario. Instead, the diverse thermal regimes projected for 2050 by the two climate scenarios led to marked differences between model responses. Aboveground biomass values simulated for the NCAR-B1 scenario remained, indeed, practically unchanged compared to the 2020 ones, whereas those simulated for Hadley-A1B grown proportionally to temperature increases, with average values for the 2050 time frame fluctuating around 63 t ha^{-1} according to the AR and year.

These results can be explained by considering the high thermal requirements of giant reed, a macro thermal species well adapted to subtropical and warm temperate environments (Pilu et al., 2013). Indeed, under baseline climate, productions were slightly penalized by constraints to photosynthesis due to sub-optimal temperatures, whereas the faster rates of tillers and leaves emission simulated for the warmer scenarios led to more rapid leaf area expansion in the first part of the season, that – in turns – increased light interception. Moreover, increased temperatures reduced the thermal limitation to solar radiation conversion.

However, since the model currently does not consider high-temperature-induced limitation to photosynthesis, the simulated increase in productivity could have been slightly overestimated.

In order to investigate the spatial patterns in future biomass projections, disaggregated data were mapped as percentage difference compared to the baseline (Fig. 3). In general, the largest increase in productivity were simulated in the central part of the Region, whereas the eastern part, where thermal conditions for photosynthesis are already close to optimum for the species, were less affected by the positive effect of the expected warmer conditions.

It is interesting to note that the highest production gains were obtained in the areas where the demand for biomass is supposed to be grater in light of the high concentration of biogas plants, representing a favourable precondition for possible investments. Given that the cultivation of giant reed in a 15-yearfield life time is estimated to cost about 10,500 € ha^{-1} (Pilu et al., 2013), the payback time of investment could be reduced from 5.5 years (baseline scenario) to 4.2 years (Hadley-A1B, 2050), if the price (about 40 € t^{-1}) at which maize fodder is currently exchanged in the local agrofuel market is applied. In light of the aforesaid low-input requirements of Arundo, benefits may also be related to the safeguard of the environment. In fact, based on Nitrate Directive(91/676/EEC), 15 out of the 16 ARs considered are identified as "vulnerable zones" to nitrate leaching, thus the use of giant reed could there represent a fruitful integration/alternative to traditional intensive maize-based cropping systems to reduce nitrogen loads. Moreover, if water scarcity issues are considered, the use of giant reed would appear even more useful also in ARs where lower production increases are foreseen, such as in south Mantua Province, in the extreme south east of the Lombardy plain. Since in this district maize cultivation is often constrained by insufficient water availability (INEA 2013),switching to a more tolerant species would contribute to water saving both directly and – to a lesser extent – indirectly, via profits reinvestment in more efficient irrigation systems (e.g., microirrigation).

4.5. Conclusions

Although *Arundo Donax* L. is increasingly considered a promising non-food energy crop in temperate climates, it is impossible to find in the literature studies aimed at evaluating its response under climate change projections. We performed here an evaluation of the mid- and long-term potentialities of giant reed cultivation in the Lombardy areas considered as eligible because of their attractiveness for investments and low risk of competition between feed and no feed crop destination. The use of a process based-model able to reproduce the morphological and physiological features of such a peculiar crop allowed to assess the feasibility of shifting to this species in case traditional maize-based cropping systems will be no longer sustainable from the economic and environmental viewpoints. Results of simulations carried out using climate change scenarios were decidedly encouraging, especially in the central part of the region, where the concentration of biogas plants is higher. The production levels forecasted for the future time frames are expected to reduce the payback time of the total investment compared to the current situation. Given the low requirements of giant reed for water and nitrogen, advantages are expected also in terms of environmental sustainability, being the study area almost entirely vulnerable to groundwater nitrogen pollution. Despite the assumptions behind this exploratory study – i.e., nutrient and water shortage effects were not considered –this study further demonstrated the usefulness of simulation models as tools able to address the needs of multiple stakeholders within the agricultural sector.

Table 1. Complete criteria-based workflow followed to identify eligible spatial units to be simulated in the Lombardy case study. 1a) spatial distribution of biogas plants by class of electric power (MW plant-1); 1b) aggregation of total nominal electric power per AR (MW); 1c) Screenshot of CropSyst model (Stockle et al., 2003)and diagram of projected temperature anomalies via GCMs until 2100 (IPCC 2007); 1d)map of most represented categories of dairy cattle farming by class of livestock per farm; 1e) distribution map of RA of interest to simulation experiment.

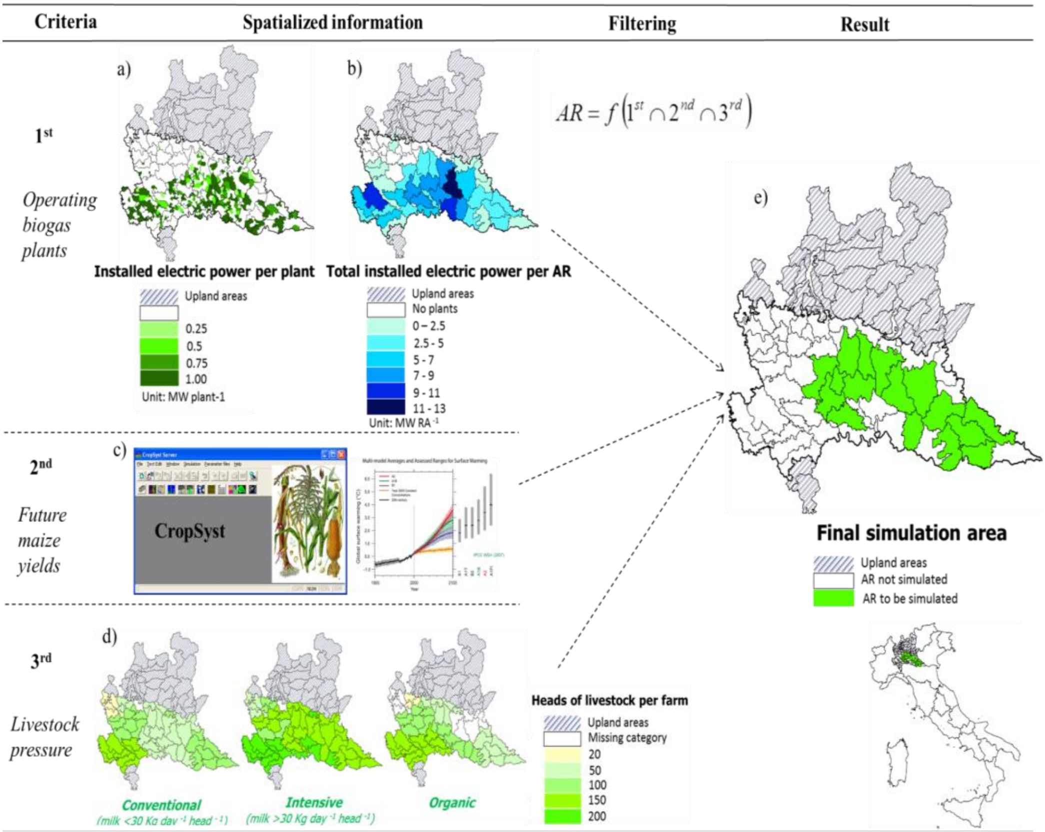


Table 2. Average daily temperature anomalies expected to 2020 and 2050, obtained by generating two contrasting scenarios (A1B and B1) according toprojections provided by NCAR and Hadley GCMs. Results were mapped as degree difference to the baseline scenario.

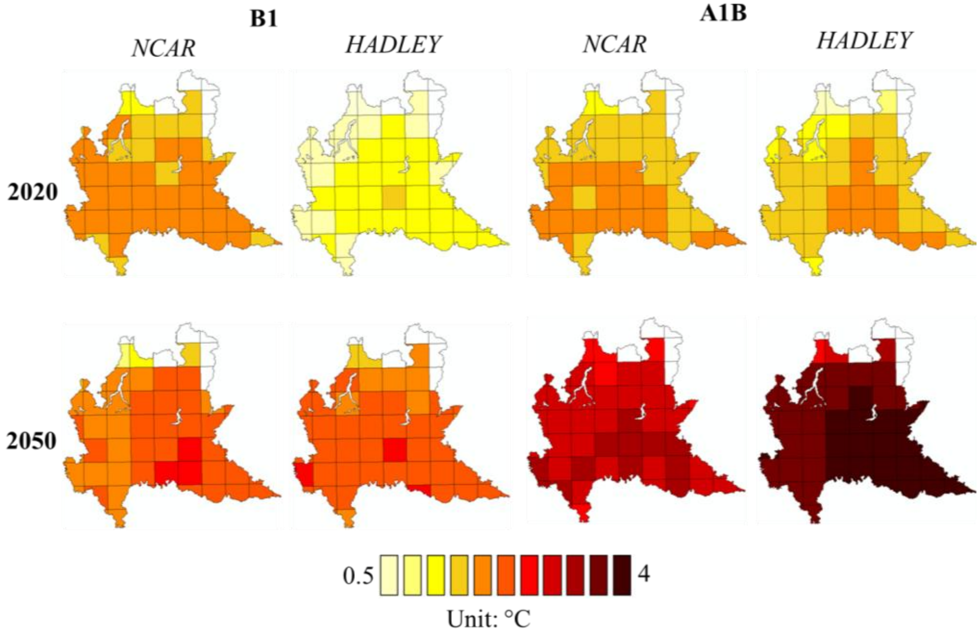


Table 3. Boxplot of absolute aboveground biomass (AGB) values simulated for baseline and future scenarios (Hadley A1B and NCAR B1). For each scenario all the AGB values obtained from the combinations year x RAwere plotted (20 x 16 = 320 valuesscenario-1).

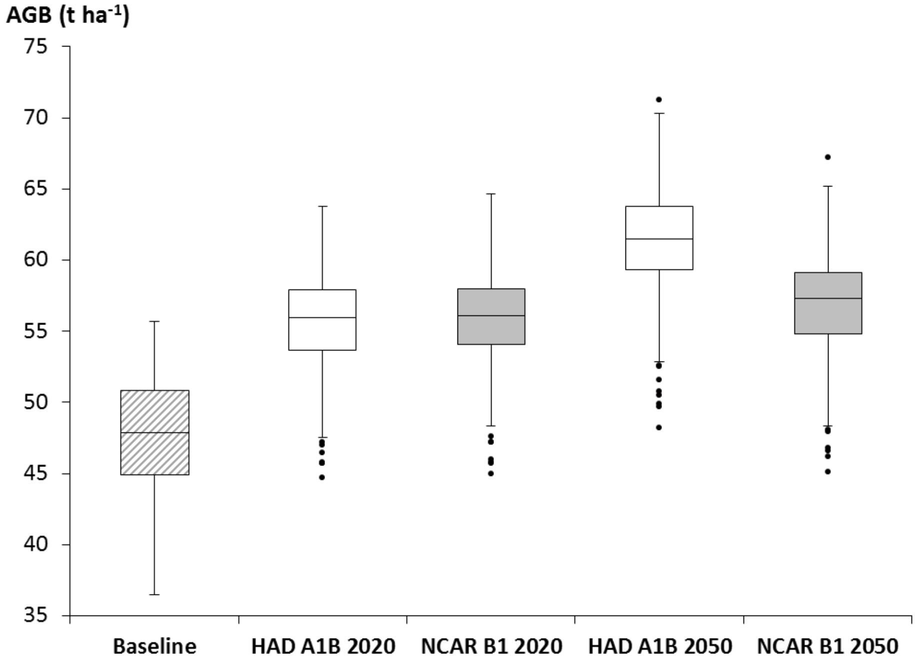
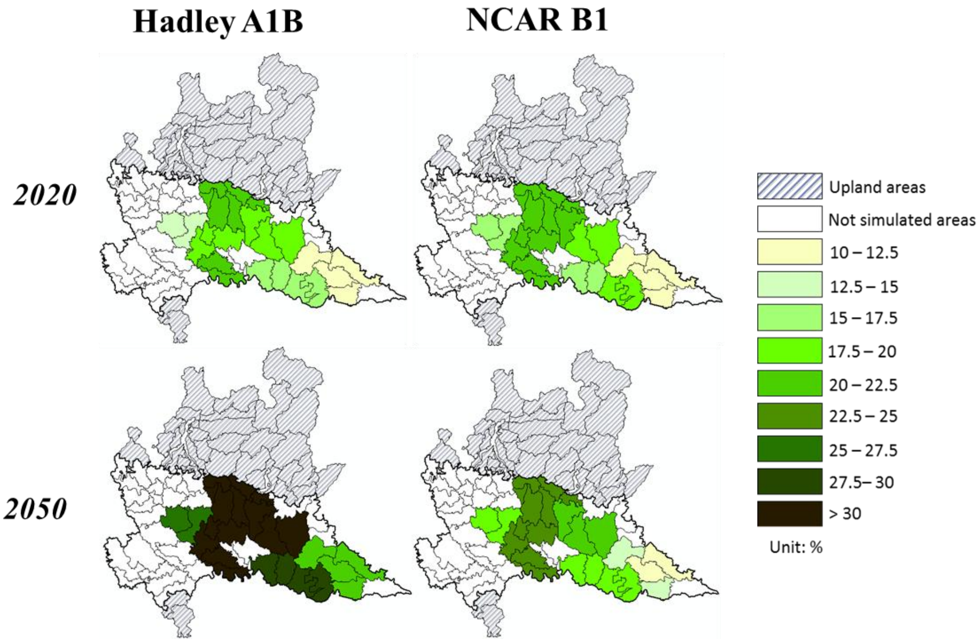


Table 4. Giant reed productivity impacts to 2020 and 2050 for Hadley A1B and NCAR B1 scenarios (potential production level). Results are shown as percentage difference compared to the baseline.



GENERAL CONCLUSIONS

This thesis proposes a process-based model to mimic the giant reed growth and development under a variety of environmental and management conditions. The model is meant to support the cultivation of this crop for bioenergy applications due to its potentiality in the investigation of different scenarios, including climate change studies.

The Canegro (DSSAT 4.5) sugarcane model was successfully re-implemented in a framework-independent component following the BioMA architecture. This implementation is targeted at providing third parties with a version of the model explicitly designed for being easily used, composed and extended, regardless of the simulation environment. Due to the similarity between the two crops, the Canegro component was effectively extended to develop the Arungro giant reed model, by sharing almost the 80% of the original code. The remaining approaches were newly developed in order to reproduce the crop behavior at tiller level and the leaf senescence process.

The lack of detailed information on the crop behavior incited the use of two dedicated field surveys (one carried out during this thesis) for the model calibration and evaluation. The field experiments allowed to simulate the crop behavior under a variety of establishment year and different sowing density. Although the observed agronomic characteristics showed a high degree of heterogeneity, the Arungro model performed reasonably good in both sites, with average agreement indices for aboveground biomass estimations in line with the one found with better-known crop models.

The climate change study of Arungro model in Lombardy region showed encouraging results for each tested scenarios, especially in the central part of the region where the high presence of biogas plants can attract the high biomass yields foreseen *in-silico*. High productive performances contribute also to lower the payback time of total investment that be done to manage a 15 year duration of the field, with best results obtained for 2050. Given the low input requirement of *Arundo d.* in terms of water and nitrogen, advantages are achieved also in terms of environmental safeguard, being the study area almost entirely vulnerable to groundwater nitrogen pollution. Despite the assumptions behind the study the usefulness of simulation models as tools for supporting stakeholders to timely face pressing constraints in a sustainable way. However further study are needed to investigate crop response to extremes events (i.e., shock form high temperature) in order to perform a more complete evaluation.

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